



School of Aerospace, Mechanical and Manufacturing Engineering

FINAL REPORT

**Mitigating the Effects of Atmospheric Turbulence:
Towards More Useful Micro Air Vehicles**

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Unclassified

18th July 2010

USAF Project number 084061: 2009-2010

Report Documentation Page			Form Approved OMB No. 0704-0188	
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1. REPORT DATE 01 OCT 2010	2. REPORT TYPE Final	3. DATES COVERED 01-07-2009 to 31-07-2010		
4. TITLE AND SUBTITLE Mitigating the Effects of Atmospheric Turbulence: Towards More Useful MAV			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Simon Watkins			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) RMIT University, PO Box 71, Bundoora, Victoria 3083, Australia, AU, 3083			8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AOARD, UNIT 45002, APO, AP, 96337-5002			10. SPONSOR/MONITOR'S ACRONYM(S) AOARD	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) AOARD-094090	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT <p>This report is the research summary of flying MAV experiments in turbulent flow, utilizing prior research measuring and reproducing aspects of the outdoor environment. Turbulence was replicated in a large wind engineering tunnel and was well mixed, thus replicating atmospheric turbulence under neutrally stable conditions far removed from local effects. Current studies are focused on using increasingly small fixed-wing and flapping-wing aircraft with IMU video tracking, and upstream flow measurements to correlate measured turbulence with vehicle disturbances. Rate, acceleration, force and pressure sensors are being evaluated to determine candidates for providing phase-advanced measurement of incipient turbulence, which can allow the aircraft to preemptively move the control surfaces to suppress attitude and position disturbances.</p>				
15. SUBJECT TERMS Micro Air Vehicles (MAVs), AltomspHEREic Turbulence Modeling, flying qualities in urban turbulence				
16. SECURITY CLASSIFICATION OF: a. REPORT b. ABSTRACT c. THIS PAGE unclassified unclassified unclassified			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 26
				19a. NAME OF RESPONSIBLE PERSON

EXECUTIVE SUMMARY

In March 2008 we proposed a 3-year plan to improve the ability of MAVs to fly in turbulent atmospheric winds. This was in-part funded by AFOSR and we are now two-thirds way through the program. Work focussed on flying experiments in turbulent flow, utilising prior research measuring and reproducing aspects of the outdoor environment. Turbulence was replicated in a large wind engineering tunnel and was well mixed, thus replicating atmospheric turbulence under neutrally stable conditions far removed from local effects.

Two series of flying experiments were conducted utilising MAVs instrumented to measure pilot inputs, actuator positions, airframe pressure distribution, and aircraft inertial responses. In both tests, an experienced pilot tried to hold straight and level flight in the centre of the tunnel. The first experiments focussed on the relative controllability and disturbance sensitivity of fixed wing versus rotary flight and also investigated configuration changes on a fixed wing craft. It was demonstrated that rotary-wing craft had better handling qualities in turbulent air compared to fixed-wing craft, which required high pilot workload to simply maintain flight. Stable level flight was easier to achieve with rotary craft, despite fixed wing being easier to fly in calm air. The fixed wing configuration changes included mass, center of gravity, moment of inertia, wing loading and span. These changes caused substantial variations in the magnitude and frequency of the aircraft responses, indicating passive changes to configuration alter the effect of turbulent disturbances. The second experiments investigated various control architectures for active disturbance rejection. Classical control strategies, including both simple and 2-DOF rate trackers, achieved substantial improvements in fixed-wing aircraft flying qualities under high levels of turbulence. Using roll rate, pitch rate, and normal acceleration tracking controllers, the aircraft was flown in controlled flight in the close wake of a bluff body in a semi-stalled condition. Improvements are expected using model-reference and turbulence-predictive dynamic inversion control strategies.

The flight experiments were augmented with supporting tests; 1) Documenting pressures and forces on aerofoils in order to examine the possibility of “feeling” through turbulent air and to also understanding the influence on averaged forces; 2) Investigating low-cost methods of video tracking – for very small craft or insects; 3) Dynamic measurements on flapping wings to see if flapping wings *per. se.* had turbulence mitigating properties compared with fixed wing, and; 4) Detailed atmospheric measurements using four probes at close lateral separation in order to understand turbulence inputs relevant to insect-sized MAVs.

Current studies are focused on using increasingly small fixed-wing and flapping-wing aircraft with IMU, video tracking, and upstream flow measurement to correlate measured turbulence with vehicle disturbances. Rate, acceleration, force, and pressure sensors are being evaluated to determine candidates for providing phase-advanced measurement of incipient turbulence, which can allow the aircraft to pre-emptively move the control surfaces to suppress attitude and position disturbances. We also suggest an international competition, which should include flying in repeatable turbulence as part of the challenge. This would assist in improving the utility of MAVs for controlled flight in the outdoor turbulent environment.

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ACKNOWLEDGEMENTS

The authors would like to thank the United States Air Force for providing financial support for this research. The assistance of the technical and administrative staff at RMIT University is gratefully acknowledged.

PERSONNEL

Professor Simon Watkins, Dr Mujahid Abdulrahim and Professor Mark Shortis have been intimately involved with the project but have had no direct or indirect salary funding from the grant. Whilst it was initially proposed to utilise a postdoctoral fellow for the work, a more cost-effective solution was to use three PhD students (as indicated by the students shown with an* below who received scholarships partially funded by the grant). These are now in the middle of their doctorates.

The work is, in many respects, due to the following RMIT doctoral student's efforts: Ben Loxton, Edward Cruz, *Mark Thompson, *Sridhar Ravi PhD, *Reuven Segal.

BACKGROUND AND AIMS

In March 2008 we proposed a 3 year experimental plan involving replication of the turbulent flow experienced by MAVs when flying outdoors on days when there is any appreciable wind. We utilised and modified a large wind tunnel in which aspects of the flow turbulence were reproduced, followed by a series of experiments flying various types of instrumented MAVs. We are approximately two-thirds way through the work, which was partially funded via the current grant. This research is part of our longer term program to understand how MAVs can best overcome the effects of turbulence in the atmospheric boundary layer and to answer some fundamental questions regarding the merits of fixed wing flight versus flapping and rotary flight.

To understand the turbulent flow environment, our prior work (e.g. Watkins, et al. 2006) gathered Atmospheric Boundary Layer (ABL) turbulence data at an elevation of approximately 4 m. Aspects of that work, including a review of prior atmospheric measurements, are given in Watkins, Thompson et. al., (2010)¹. We then showed that aspects of turbulent flow relative to a flying MAV could be replicated in a very large wind tunnel (e.g. Watkins, Abdulrahim et. al. 2010) and examined the effects of the ABL turbulence on the pitch and roll responses of an MAV. Our studies showed that the responses of an MAV

¹ Copies of relevant papers are appended to this report, providing further technical details.

could be significantly influenced by the ABL turbulence characteristics, such as the turbulence intensity and length scales.

An aligned project, AOARD-06-4037 was initiated to understand the effects of turbulence on thin wings. Its first phase was to generate approximately homogeneous turbulence with intensities ranging from 1% to 15% and of various integral length scales in two large wind tunnels. The second phase was to investigate the effects of turbulence in a 2-D test of a typical airfoil. This work has been extended by Sridhar Ravi who is investigating the influence of large scale ($> 1\text{m}$) turbulence of the performance of Low Reynolds number thin aerofoils. Interim results are given here and have been presented at the World Congress on Engineering, Imperial College, UK, July 2010 (Watkins, Ravi et. al., 2010).

As part of a European visit in 2009, outdoor turbulence measurements were made in conjunction with the Oxford Animal Flight Group in the UK. This involved taking four point turbulence measurements at a variety of lateral inter-probe spacing (from 450 mm down to 14 mm) and in various wind conditions and terrains. This is part of on-going work by the PhD student Mark Thompson. A conference paper which described research investigating the potential roll inputs as a function of span was presented at the 25th Unmanned Air Vehicles Systems Conference in Bristol UK (Thompson and Watkins, 2010). Interim results are also presented here.

Progress on our work has been reported at several conferences where AFOSR personnel have been in attendance. This was supplemented via presentations at the NATO AVT-186 meeting in Portugal 20th – 24th April, 2009, and at Wright Patterson and Eglin USAF bases in April 2010, both funded by Window on Science grants.

OVERVIEW OF CURRENT WORK

Our plan for the duration of three years involved flight experiments and several adjunct experiments. The framework for this is given in Figure 1.

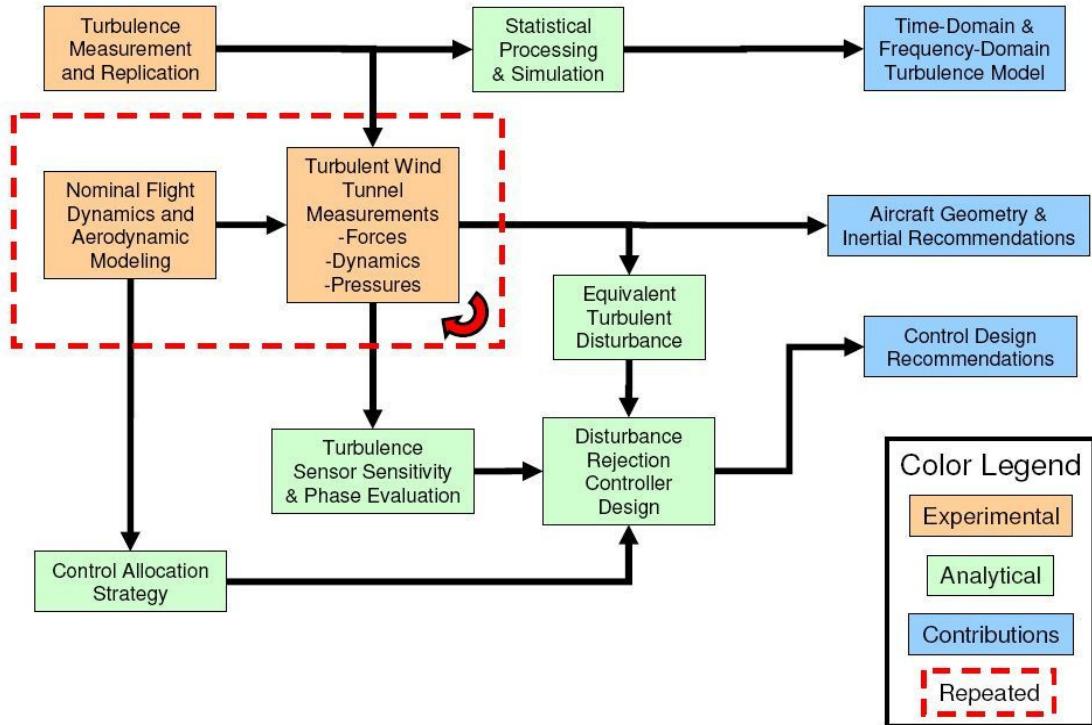


Figure 1 Framework of enabling technology for enhanced MAVs

Flying Experiments

These were undertaken via two series of flying experiments at the Monash University Wind Tunnel in Victoria, Australia, with the first being an initial comparison of the relative merits of fixed versus rotary wing flight in replicated turbulence. This was followed by a second series of experiments focussing on fixed wing flight with various levels of closed loop systems based on closed-loop control strategies utilising dedicated on-board data acquisition systems (DAQs), processors and commercial off the shelf (COTS) IMUs.

Adjunct Experiments

Our adjunct experiments included:

- 1) Investigating the dynamic pressures on the surfaces of thin 3-D and quasi 2-D aerofoils and dynamic force measurements on an isolated wing. These experiments were undertaken in order to investigate the possibility of using additional sensory

inputs to hold MAVs in straight and level flight. It was hoped that these biomimetically inspired methods might offer some “time-forward” advantages over conventional inertial measurement unit (IMU) systems and could replicate avian agility for future MAVs by “feeling” their way through turbulent air.

- 2) Trialling low-cost methods of video tracking for documenting the motions of the smaller MAVs (including a locust) which could not carry our data acquisition systems.
- 3) Performing an initial study of a simple flapping wing model fixed to a specially designed dynamic force balance with concurrent measurements of upstream turbulence documented at four laterally-separated points.
- 4) Further measurements of outdoor turbulence at smaller inter-probe spacing than our prior research.

The work was funded for 12 months. In this report we summarise work to date and future plans.

WORK AND OUTCOMES TO DATE

1) Flying experiments. To date we have replicated relevant aspects of the turbulent flight environment in two large wind tunnels; The RMIT Industrial Wind Tunnel, which has a working section size of 3m (wide) x 2m (high) x 9m (long) and the tunnel based at Monash University which has two working sections; an open jet section (which has relatively smooth airflow and is surrounded by a plenum chamber of relatively still air) and a larger upstairs test section, in which the majority of the flying experiments were carried out, of size 12m (wide) x 4m (high) x approximately 50m long. We showed that aspects of the turbulent flow domain experienced by MAVs flying outdoors could be replicated in the tunnel (Watkins et. al., 2008 and 2010), thus providing a facility in which various repeatable level of turbulence could be generated, within a useful range of turbulence intensities and scales. Two series of experiments were conducted where instrumented MAVs were flown. These are described here and in appended publications.

Series 1 Flying Experiments – Aircraft Configuration Study.

In January 2009 Dr Abdulrahim came to Australia to fly a variety of fixed wing and rotary craft in the Monash Tunnel, augmented with a series of outdoor flight experiments. The craft were instrumented to measure the six DOF responses with specially developed IMU data unit acquisition packages. These could record pilot control inputs and had the ability to input several auxiliary channels to enable sensory inputs (such as pressure sensing on wing surfaces and strain measurements of spars) to be investigated at a later date.

An Atmel microcontroller unit (MCU) provided the overall system control, timing and user interface. Data frames, processed by the MCU, were written to an onboard flash memory module at a sampling rate of 100Hz. Single-pole analog RC filters (characteristic frequency 5 Hz) were used on each of the 16 input channels to filter noise and vibrations from the flight data measurements. Actuator positions were determined for ailerons, elevator, and rudder control surfaces by measuring the analog voltage on the position feedback potentiometers in each servo motor. This potentiometer was used internally for closed-loop position tracking and provided a convenient measurement of the output arm motion. Measurement of the actuator position was made without adversely affecting the operation of the servo.

The piloting aim for these wind-tunnel studies was to attempt to hold the craft in a relatively steady position, whilst being subject to replicated atmospheric turbulence. Despite the test section being relatively large (12m wide, 4m high 50m long), flying in turbulent flow was very challenging and resulted in many terminal departures. One of the main findings from pilot feedback (via the Cooper-Harper rating system) was that fixed wing craft were relatively easy to fly in smooth flow but became extremely difficult to fly in levels of turbulence of over about 7% (Loxton et. al. 2008 and Watkins, Abdulrahim et. al., 2009).

The influence of fundamental vehicle parameters on turbulent response and handling qualities was further investigated for a selected fixed wing MAV. This craft, shown in Figure 2, was a relatively highly powered, lightly mass-loaded and highly responsive 1m span model modified to carry the IMU and DAQ. Tests included systematically varying the configuration

including; mass, roll moment of inertia, wing span and wing loading. The details of the instrumentation, sensors, tests analysis and results can be found in the (appended) paper submitted to the AIAA Journal of Aircraft (Abdulrahim, Watkins et. al., 2010). The analysis focussed on identifying a linear dynamic model of the aircraft via frequency sweeps and control doublets (manually input by the pilot) in calm outdoor conditions and then comparing predicted aircraft response (from the dynamic model) with measured response in the turbulent wind tunnel tests.

From the outdoor tests, output-error method system identification techniques were used to estimate the lateral and longitudinal stability and control derivatives. This step included estimated sideslip and angle of attack using the known (exact) kinematic equations.

From the wind-tunnel tests a form of the kinematic equations was used to compute the forces and moments sustained by the aircraft during the test. Then the control time-histories (aileron, elevator, and rudder) were used to simulate the dynamic system estimated from the outdoor flight tests. This process generated state time histories (roll rate, pitch rate, lateral acceleration, vertical acceleration etc.) that exhibited what the aircraft response would be in open-air flight if subject to the control inputs from the wind tunnel. Predicted forces and moments were computed using the kinematic equations for the simulated aircraft response. The measured and predicted forces and moments were differenced to yield a residual which approximated the forces and moments imparted on the aircraft due to turbulent disturbances. The time-histories of the forces and moments were used as input to a dynamic inversion of the aircraft control effectiveness matrix to determine the equivalent control deflections. The resulting control time histories approximated the aileron, elevator, and rudder deflections that produce forces and moments equivalent to those experienced in turbulence.

The control equivalent turbulence disturbance (CETD) from a 40-second flight segment for each configuration was represented as both a histogram and a power spectral density of the equivalent control deflections. Thus the CETD provided insight into the turbulence sensitivity of configurations that included; a) the inherent sensitivity of an aircraft configuration; b) effectiveness of the control surfaces in counteracting the disturbances; and c) the actuator magnitude and bandwidth that would be required to move the controls.

Comparisons of the various control configurations revealed known trade-offs, such as the beneficial effects of aircraft mass and wing loading on attenuating force disturbances. Other results were less obvious, such as the influence of roll moment of inertia on equivalent aileron requirement, where increased moment of inertia resulted in increased equivalent aileron, despite the effects of inertial roll stiffness.

Increased wing area caused a decrease in low-frequency equivalent elevator with constant wing loading, but resulted in increased elevator with constant mass. For the constant mass configurations, the decrease in wing loading that accompanies an increase in wing area contributes to the pitch divergence tendency at low frequencies. Interestingly, in all other metrics apart from pitch, the reduced wing loading appears to decrease the influence of

turbulence on the aircraft. It is the smaller, more heavily loaded configuration that is the most sensitive.

The results fall short of defining the ideal aircraft design for high turbulence environments, but demonstrate the sensitivity of classical aircraft sizing parameters on the response to turbulent disturbances. The configurations less affected by disturbances can be taken as approximate guidelines for preliminary designs of new UAVs. Alternatively, the more sensitive configurations can be used as benchmarks to test closed-loop disturbance rejection strategies, whose aim may be to exploit performance benefits while mitigating inherent turbulence sensitivity.

Series 2 Flying Experiments – Varying Degrees of Closed Loop Control

In these tests we again focussed on the fixed wing craft and made outdoor and wind-tunnel flight tests, where we investigated various levels of closed loop control. To simplify the process, dedicated rigs that reduced the degrees of freedom were utilised. Figure 2 depicts the pitch/heave and roll rigs. These enabled relative ease of movement in certain freedoms; for example on the pitch/heave rig vertical cables, laterally separated by the aircraft span, restrained the craft in all but the heave translation and pitch rotation. Tests involved uncontrolled motions (i.e. under the influence of free-stream turbulence) as well as under varying degrees of piloted and automated control.

The test rigs permitted study of several control strategies in the turbulent wind tunnel without risking damage to the aircraft model. The roll rig allowed the aircraft to rotate freely about the longitudinal axis while control gains were tuned. Motion about the roll-axis is typically decoupled from other lateral modes and longitudinal modes. Controllers tuned on the roll-rig were subsequently flown untethered in the tunnel with excellent performance.

A simple roll rate tracking controller reduced departure tendency and improved handling qualities, although the pilot workload remained somewhat high due to coupling between the command response and disturbance rejection. A subsequent 2-DOF control design allowed separate tuning of the pilot and turbulence responses. Filters placed in the feedforward and feedback paths allow independent tuning of the response transfer functions from command and disturbance inputs. The feedback filter and gain are tuned to allow the controller to respond rapidly and with full authority to roll disturbances caused by helical flows. A lower-frequency feedforward filter limits the command rate to preserve piloted handling qualities and provides frequency separation when used within a guidance and navigation system.

Control deflection magnitudes predicted using CETD are substantially smaller than those incurred during piloted flight. This result is not surprising, since the inherently phase-delayed pilot inputs both reject disturbances and generates additional control acceleration to return the aircraft to the trimmed condition. CETD provides only the control magnitude needed to overcome the disturbance. Improved control response can be achieved by using phase-advanced sensors or by using feedforward inputs from the real-time computation of CETD. Uncommanded accelerations would be opposed by control action computed from an

inverse model of the control effectiveness. The standard feedback control behavior would account for residual response errors.

Longitudinal controllers were tuned by flying the constrained aircraft model on two highly-tensioned cables mounted between the floor and ceiling of the test section. Guides installed at the wingtips allowed the aircraft to rotate about the pitch axis and translate vertically along the cables. An inner pitch-rate tracking loop was designed to stabilize the short period mode and reject pitch disturbance using a 2-DOF controller architecture. Pitch rate commands were generated by an outer-loop vertical acceleration tracking controller, which was a simple 1-DOF controller with a command scaling gain.

Wind tunnel flight tests of the vertical acceleration, pitch rate, and roll rate tracking controllers showed large improvements in handling qualities relative to open-loop flight. The relatively-simplistic controllers were promising, although tracking errors persisted, despite high-bandwidth actuator usage. Ongoing control design efforts are focused on implementing CETD as a means of compensating for disturbances using a predicted response. Such controls, and other model-reference adaptive approaches, will be tested in turbulence levels in which open-loop flight is not possible. The controllers will also be tested in the close wake of bluff bodies, where local turbulence effect dominate the continuous, mixed flow of the wind tunnel test section



Figure 2 a) Pitch/heave rig and; b) the roll rig

Adjunct Experiments.

1) Dynamic pressure and (via integration) force measurements on thin aerofoils

Based on the work of Mueller (1999) a thin flat plate airfoil was selected. This airfoil produces well-documented regions of laminar separation and reattachment at the leading edge. The aerofoil, shown in Figure 3, is 2% thick, has a chord of length 0.150m a super-elliptical leading edge and a tapered trailing edge. Due to the fragility and flexibility of the aerofoil it was necessary to use guying threads to avoid excessive vibration. As these were well-removed from the location of the pressure taps the aerodynamic effects were considered negligible, see Figure 4.

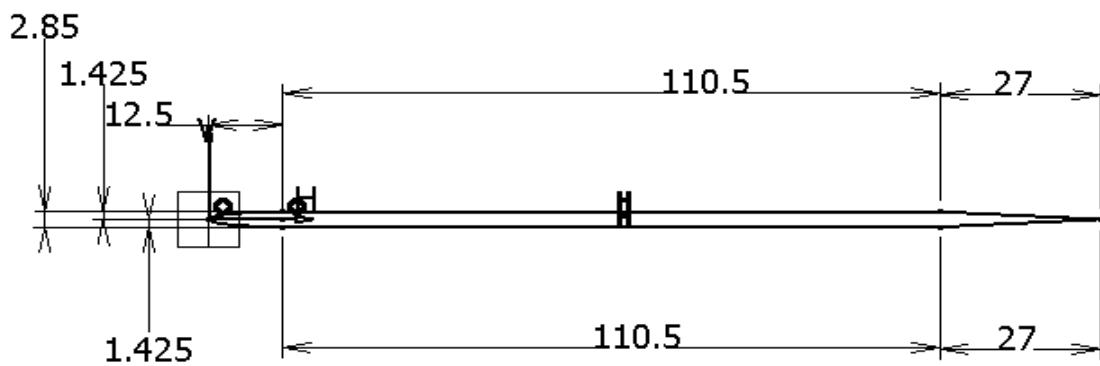


Figure 3 – Airfoil section, all dimensions in mm

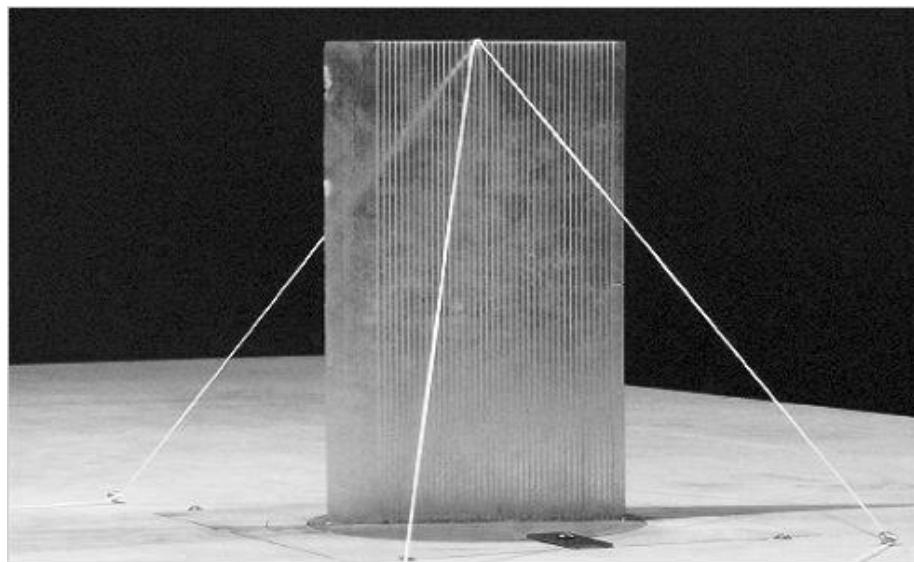


Figure 4 – Prototyped 3-D wing with integral pressure taps.



Figure 5 Prototyped 2-d wing between end plates in the Monash tunnel

Wings were manufactured using a rapid prototyping method with integral surface pressure taps. Pressure measurements were made using the Dynamic Pressure Measurement System (DPMS) manufactured by Turbulent Flow Instrumentation (TFI). This system digitally measures pressure signals on 60 channels. The pressure-tapped wing consisted of 40 channels for both 2-D as well as 3-D tests. Tubing of 1mm internal diameter was used to connect the integral pressure taps to DPMS module. For 2-D tests, the tubing length used was 500mm and for 3-D tests the tubing length was 300mm. A (relatively small) dynamic correction was used to enhance the frequency response giving an essentially flat amplitude response to several hundred hertz. This was well above any frequencies of interest (see later). Digital data acquisition was by a National Instruments 6032E DAQ card in a PC.

A nominally 2-D test configuration utilised a 900mm long version of the aerofoil described above, mounted between end plates with four guying threads, as shown in Figure 5. Pressure measurements were taken at 2 spanwise stations separated by 200mm simultaneously over the wing at 20 chord wise locations. Results are only presented here for one spanwise location; the other series of taps are being used to investigate spanwise correlations (part of on-going work). No pressure taps were located on the pressure (underside) of the airfoil for the 2-D configuration; these pressures were gathered later by setting the aerofoil to a negative angle of incidence.

A 300mm span version of the airfoil without end plates was used for the 3-D tests. Fluctuating pressures were measured at midspan using 20 pressure taps each on the top and bottom surfaces of the wing. Due to the need to maintain a large test section area for the generation of turbulence, the wing was mounted in the RMIT Industrial Wind Tunnel in an open-ended configuration supported on the bottom (see Figure 4). A 3-D open ended configuration provided a simpler solution that gives a more realistic representation of a real MAV wing. It was shown that whilst the flow around the wing is inherently 3-D in nature, at the location of the pressure taps the flow is similar to the 2-D case. This was established through the use of flow visualization where it was shown that at the location of the pressure taps there was little influence on the flow structure from the wing tip vortex, and there was minimal spanwise flow.

The surface pressure data were processed to give the pressure coefficient (C_p) distribution over the airfoil for each test condition. A large volume of data was generated and a full set of results will be published in the doctoral theses by Loxton and Ravi (in press). However key findings are summarized here with a more complete set of results provided in the publication by Watkins et al (2010) appended to this report.

The time-averaged variation of the pressure coefficients as a function of chord were found to be significantly influenced by turbulence intensity, particularly around the stall region. An example of this can be found in Figure 6 where the pressure distribution indicates that the wing has just stalled in relatively smooth flow (1.2% turbulence intensity) whereas at the elevated turbulence levels of either 7.4 or 12.6% the flow appears to be well attached.

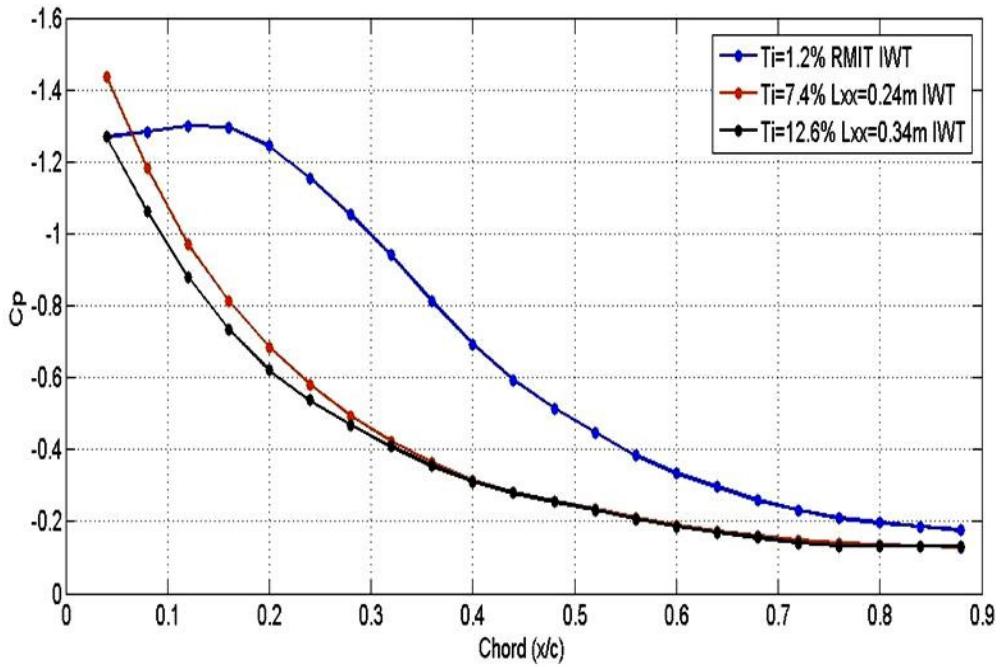


Figure 6 – Pressure coefficient distribution over airfoil at 6° for different levels of turbulence

The effect of turbulence on time-averaged pressure coefficients over a wide range of angles, including the stall region, can be seen by comparing the results in Figures 7 and 8. Negligible hysteresis effects were found.

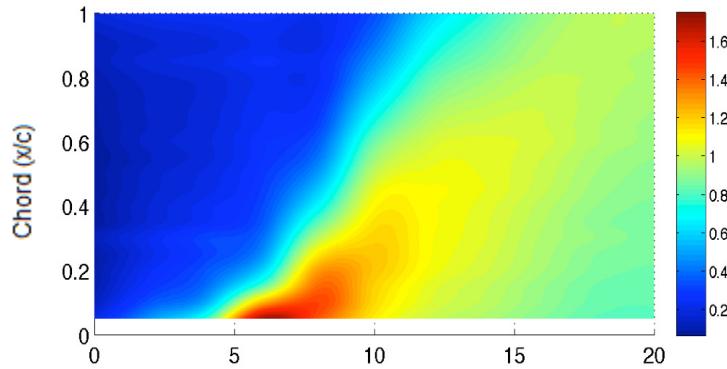


Figure 7 – Time-averaged pressure coefficient distribution as a function of angle of incidence for 3-D wing in nominally smooth flow (1.2% turbulence intensity)

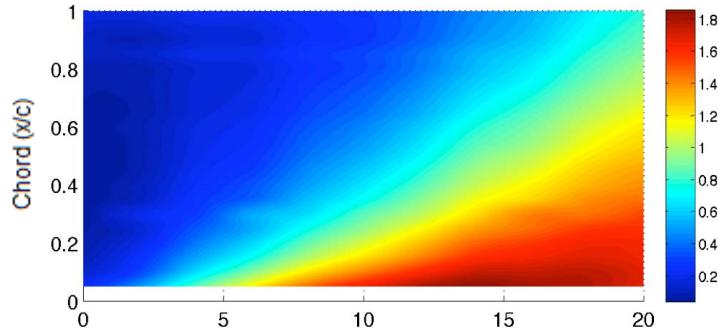


Figure 8 – Time-averaged pressure coefficient distribution as a function of angle of incidence for 3-D wing in $T_i=12.6\%$ and $L_{xx}=0.34\text{m}$

The influence of turbulence on the standard deviations of the pressure fluctuations can be seen in Figures 9 and 10 (note the difference in C_p scaling between the plots). Further details of the dynamics of the pressure fluctuations can be observed in spectrograms of the C_p in one of the attached papers (Watkins, Ravi et. al., 2010), where the influence of turbulence is shown to significantly contract the length of the laminar separation bubble.

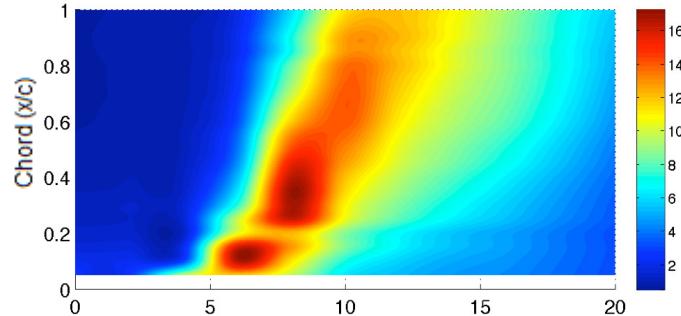


Figure 9 – Standard deviation of pressure fluctuations for 3D wing when $T_i=1.2\%$ and $L_{xx}=0.34\text{m}$

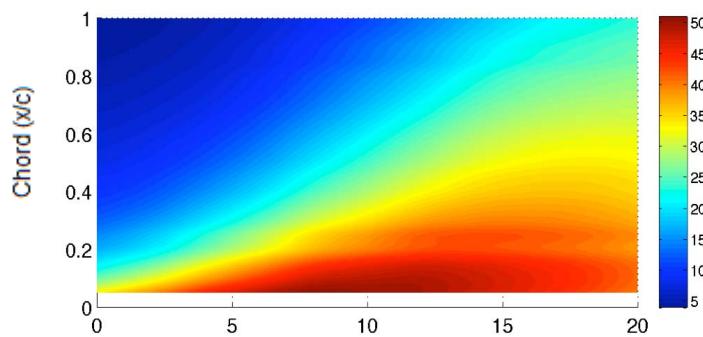


Figure 10 – Standard deviation of pressure fluctuations for 3D wing when $T_i=12.6\%$ and $L_{xx}=0.34\text{m}$

From the 2-D experiments conducted in the two different wind tunnels it is possible to investigate the influence of turbulence integral length scale under nominally similar intensities. Figure 11 depicts the effect of both turbulence intensity and scale on the lift-curve slope.

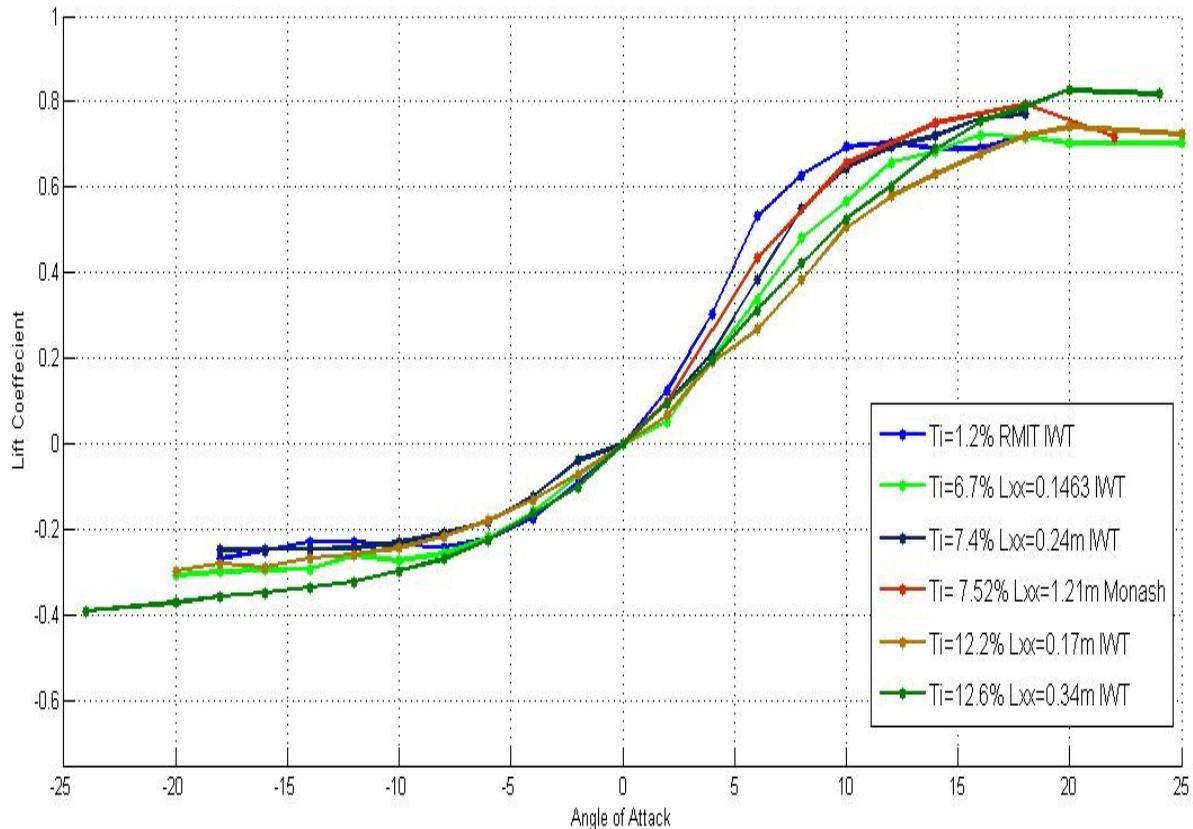


Figure 11 Suction side lift coefficients versus angle of attack plot of airfoil with different turbulence intensities and length scales

The general conclusions that can be drawn from the on-going research on the influence of turbulence on flat plate aerofoils is that changes in integral length scale and turbulence intensity both have significant influence on thin flat-plate aerofoil performance – dynamically and when data are time-averaged. The following specific points can be made:

- Increasing the turbulence intensity shortens the length of the laminar separation bubble, increases the maximum lift coefficient and reduces the lift curve slope, and;
- As the integral length scale increases (at nominally similar intensity) the lift curve slope gradient increases trending towards the smooth flow condition.

Initial attempts at measuring the dynamics on an entire wing via a (relatively stiff) six DOF force balance proved unsuccessful due to the system dynamics strongly influencing the measurements. With lighter models this should prove less problematic.

2) Low Cost Video Tracking Investigation

The use of multiple video cameras to accurately track the location and attitude of aerospace models in wind tunnels is a well established technique but generally utilises large numbers of relatively costly cameras. In the recent tests, video tracking of small aircraft models was carried out to allow the derived 3D position and attitude changes of the aircraft to be compared with the onboard DAQ modules using six domestic video cameras. The video tracking approach has proved to be feasible for future research on smaller aircraft models or insects that might not support the weight of even the smallest DAQ.

Two approaches were tested. One configuration used multiple cameras tracking fixed and rotary wing models to determine the full six degrees of freedom of the model. The second consisted of a single camera to determine the position and roll angle of a fixed wing model.

In the first instance, six video camcorders were rigidly mounted to the ceiling of the wind tunnel. The configuration was designed to provide a reasonable coverage of the flight volume while still giving a resolution of 3-5 mm for lateral movements and 0.5 degrees for rotations. Retro-reflective targets were placed in a grid pattern on the floor of the tunnel to provide highly visible points to determine and continuously monitor the relative locations and orientations of the six cameras. Retro-reflective targets were placed on the flight surfaces of the fixed wing craft, and on the undercarriage of the helicopter, to enable tracking of the position and attitude of the vehicles relative to the base plane of the wind tunnel. Synchronisation was achieved using a flashing LED placed in view of all cameras and with the use of an external flash gun at random times throughout each test. Selected image sequences from the six camcorders were then analysed.

This first experiment had limited success, primarily due to exposure problems and interlace effects, but particularly due to insufficient coverage and overlap provided by the camcorders (see Figure 12). As noted previously, flying in turbulent flow was very challenging and the expected measurement volume proved to be an under-estimate. This weakness in the configuration could be readily overcome with specifically procured video cameras and the experience gained from this initial test.



Figure 12. Example of coverage from a video sequence of the fixed wing model.

The second experiment was based on a simplified configuration of a single, inexpensive web cam placed on the floor, upstream from the test volume. The position and orientation of the camera was determined using retro-reflective targets fixed to the floor and ceiling of the wind tunnel (see Figure 13). The experiment involved a fixed wing aircraft, which allowed forward-facing, red LEDs to be mounted on the wing tips. Real time software was developed to track the LEDs within the image space. Rapid identification of the LEDs was facilitated using a red filter on the camera, thereby muting other light sources, and isolating the circular images using a Canny edge detector with constraints on the image separation and target image size (see figure 13). The web cam was operated at 15 frames per second and a resolution of 800 by 600 pixels to limit dropped frames in the real-time processing.

Knowing the separation of the LEDs, the position of the aircraft within the wind tunnel section, as well as the roll angle of the aircraft, could be accurately estimated. Angle of attack and yaw could not be determined from this set-up, however these parameters were considered to be of lesser priority. Error analysis indicates that the position of the aircraft model is determined with a precision of a few millimetres.

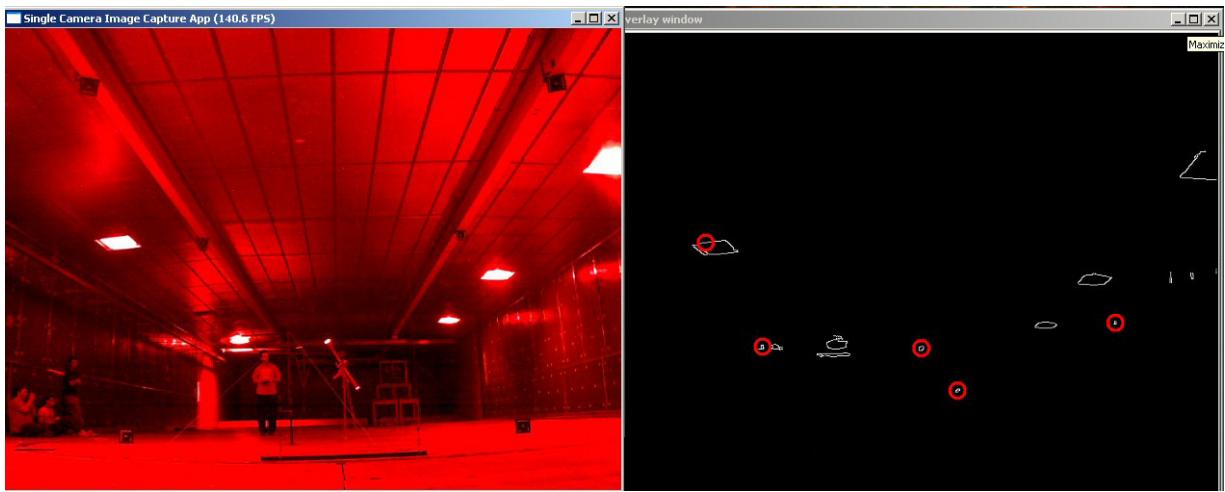


Figure 13. Target tracking of model on the roll rig - web cam image on the left, true and false targets identified on the right. Fixed targets on the floor and ceiling used for the camera set-up are visible in the left hand image.

Initial tests were also carried out to determine the feasibility of tracking the wings of a locust in a small wind tunnel. A consumer grade video camcorder with a 240 frames per second mode was used to capture sequences of a tethered locust (see figure 14). As predicted by other research, the locust responded to the air flow by flapping, in these tests at a wing beat frequency of 18-19Hz. Structures in the wings are evident even in these low resolution images, demonstrating that it would be feasible to track the wings very accurately with a good quality, high speed video camera. With multiple cameras a 3D path of the wings could be determined enabling studies of the response of insects to turbulence and discrete gusts.



Figure 14. Still image extracted from the 240fps video sequence of the locust.

3) Dynamic Measurements of Flapping Wing Flight

An initial study of a simple flapping wing model fixed to a specially designed dynamic force balance was undertaken, including some concurrent measurements of upstream turbulence documented at four laterally-separated points. This was to compare lift generation methods and roll inputs via flapping flight to conventional fixed wings in turbulent flow. For some tests the wings were fixed rigidly and the model was angled to give the same lift force as the time-averaged lift force found in the flapping tests. The aim here was to investigate whether there were mechanisms involved in flapping flight that mitigated the deleterious effects of turbulence, particularly in the troublesome roll inputs we had experienced when flying MAVs in turbulence. This work is on-going, including measuring inertial loads in the absence of air and it was identified that there was a requirement to increase the frequency response of the force balance (or reduce the mass and moments of inertia of the test models) when loaded with our (relatively heavy) MAV, see Figure 15. However it was demonstrated that the balance would be well suited to investigating the dynamics of lighter models (e.g. the DelFly from the University of Delft). These could be made in conjunction with concurrent measurements of the incoming turbulent flow.



Figure 15 The flapping wing model on the dynamic force balance.

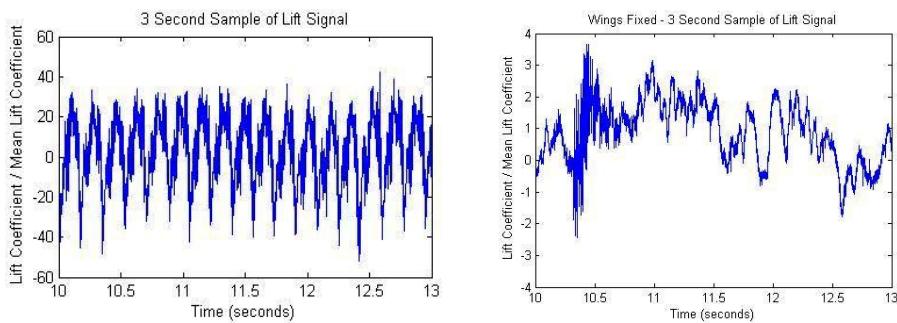


Figure 16 a) Non-dimensional lift coefficient for the flapping model at ~ 6 Hz, and; b) Non-dimensional lift coefficient with wings fixed.

4) Further Measurements and Analysis of Outdoor Turbulence Relevant to Insects

Utilising the multi-hole Cobra probe system used in our initial outdoor measurements (Watkins et. al. 2006) we took more detailed wind data where we varied the inter-probe spacing down 14mm – this spacing being more representative of spans relevant to insects.



Figure 17 Outdoor measurements with varying inter-probe spacing

To obtain a measure of the magnitude of the differences between instantaneous flow measurements, the standard deviations of differences between probe measurements were calculated. This produced 6 values for each data set, those being the differences between probes 1-2, 2-3 and 3-4 at the probe spacing, 1-3 and 2-4 at twice the probe spacing and 1-4 at three times the probe spacing. This was done for both the longitudinal velocity and the pitch angle and typical data can be seen in Figures 18 a) and b).

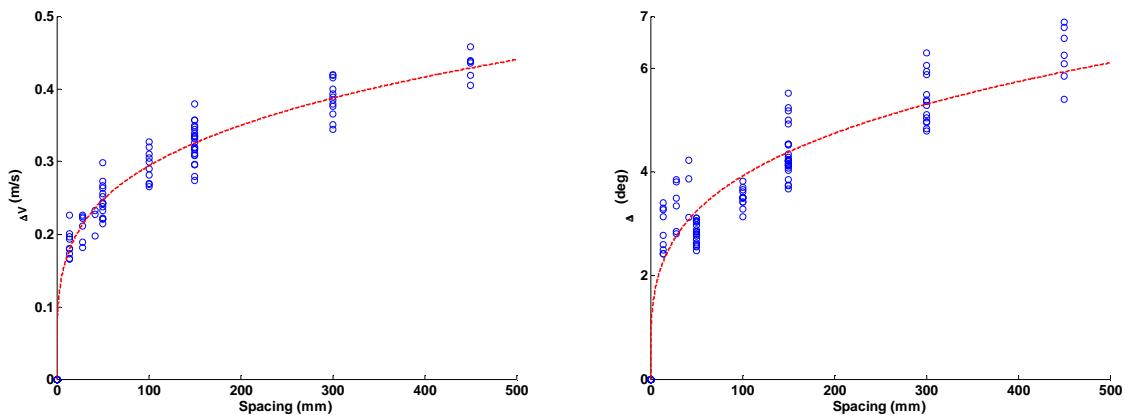


Figure 18 Standard deviations versus lateral separation for; a) longitudinal velocity magnitude, and; b) pitch angle

From these data sets we used a simple strip theory model to investigate the variation on the potential roll inputs as a function of simulated wingspan, where the standard deviations of the fluctuating lift coefficients are plotted as a function of spacing. The results roughly followed a power law as shown in Figure 19.

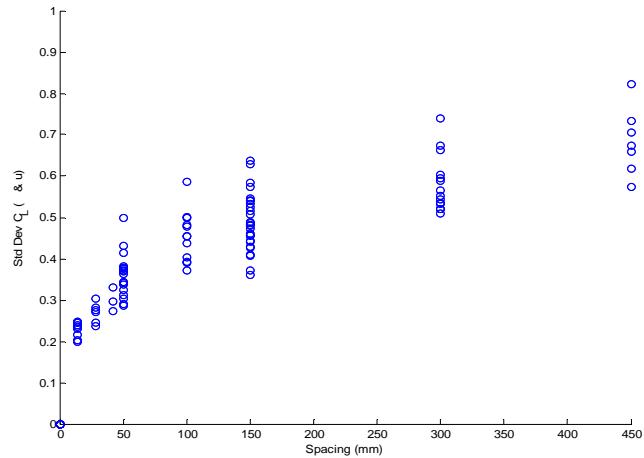


Figure 19 Standard deviations of lift as a function of simulated arising from combined pitch angle and velocity magnitude variation.

Since the potential roll resistances for any real aircraft scale in a highly non-linear manner (e.g. the roll moment of inertia is proportional to the wing mass and span squared) it is considered that the influence of turbulence on roll will significantly increase as span reduces. This is part of on-going work and has been described in detail in one of the appended papers (Thompson and Watkins, 2010).

CONCLUDING REMARKS

The outdoor measurements highlight the complex nature of the flow environment, particularly for the smaller span craft flying through the atmospheric boundary layer. The resulting turbulent flow environment generates rolling inputs that are challenging and these dynamic inputs increase as span reduces.

From the flight test experiments in turbulent flow we have isolated some effects of configuration, including mass, moment of inertia, wing loading and span. These were shown to exhibit substantial variations in the magnitude and frequency of the aircraft responses. Some obvious relations were confirmed, such as the effect of increased roll moment of inertia on roll time constant. In other cases, the effect of a parameter change, such as wingspan, was not entirely clear. Analysis of these results is continuing with both statistical and physical approaches.

The methods used to estimate turbulence from the measured versus predicted forces and moments showed that passive configuration change can be used to alleviate the effect of turbulence in flight. Representing the turbulent disturbance as a series of equivalent control inputs or as equivalent state disturbances affords direct insight into the effect of the turbulence on the aircraft and provides mitigation strategies.

The ongoing flight-test research on fixed wing craft is focused on developing a series of design recommendations for each of the fundamental aircraft parameters. These recommendations are in the form of trade-offs between flight performance in smooth and turbulent air. The disparate factors of open-loop stability, trim drag, control effectiveness, and inertial stiffness can have beneficial effects in one flight regime that are detrimental in the other. Such data will enable the aircraft design to achieve a desired level of inherent resistance to turbulent disturbances. These have led on to initial flying experiments under closed-loop control which appear to have great potential for reducing the deleterious effects of turbulence on the smaller fixed wing craft.

From our related work on the effects of turbulence intensity on the time-averaged performance of airfoils we have shown that the stall is delayed and the lift curve slope is reduced as intensity increases. Integral length scale was also varied (up to many times the airfoil chord width) and was shown to also influence airfoil performance. We also investigated the time-varying pressures on the airfoil surfaces and are attempting to link these with upstream measurements of turbulence in order to investigate the use of wing pressure or strain sensors to “feel” a way through turbulent air.

A complementary aspect of the ongoing research is in the development of control strategies for mitigating the effects of turbulence on fixed wing craft. Such strategies will include requirements on the selection of turbulence sensors, particularly with regard to the phase response merits of inertial, aerodynamic, force, strain and pressure sensors. The control equivalent disturbance analysis presents direct requirements for control surface design and allocation for full authority control of the aircraft forces and moments.

RECOMMENDATIONS AND FUTURE PLANS

Our proposals for further work fall into three complementary areas:

- 1) Continue developing and testing control strategies for mitigating the effects of turbulence on fixed-wing aircraft flight. Candidate control architectures include classical designs, which could use a 2-DOF loop structure to separate the command and disturbance responses. Alternatively, a dynamic-inversion approach could be used to implement real-time control equivalent turbulence disturbance analysis, in which a model reference is used to separate expected response for disturbance response. The residual forces and moments caused by turbulence would be rejected using the dynamic inversion, which computes the necessary opposing control surface deflections. The research would include study of alternative turbulence sensors, which could include accelerometer arrays, distributed pressure sensing, or wing bending moment transducers. The controllers can be implemented on reduced-scale fixed-wing aircraft using a newly-developed 5-gram IMU and control system. Video tracking can be used to provide attitude and position data during wind tunnel tests, allowing implementation of full autopilot capability.

- 2) Understanding the transfer functions between the upstream flow turbulent characteristics and surface pressures and forces developed on thin wings – both for fixed wing and flapping craft. The rationale behind this is to provide phase-advanced information for pre-conditioning the craft to minimise the effects of turbulence. We have developed a pressure-tapped flapping wing model for this research and have a dynamic force balance that should be suited to some of the smaller flapping craft such as the DelFly.
- 3) Document the response of tethered insects to gusts based on our simple video tracking system and ability to generate and document gusts directly upstream of locusts.

We also suggest an international competition which should include flying in repeatable turbulence as part of the challenge. This would assist in improving the utility of existing MAVs for controlled flight in the outdoor turbulent environment.

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APPENDIX ONE: Paper from the Royal Aeronautical Journal

APPENDIX TWO: Paper from the World Conference on Engineering

APPENDIX THREE: Paper submitted to the AIAA Journal of Aircraft

APPENDIX FOUR: Paper submitted to the International MAV Journal

APPENDIX FIVE: Paper from the 25th International UAVS Conference